



Biomechanical Analysis of Movement and Knee Injury Risk in Football Athletes Using Three-Dimensional Motion Capture System

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Abstract: Knee injuries represent one of the most prevalent and debilitating musculoskeletal conditions affecting football athletes worldwide. This study aimed to analyze the biomechanics of lower extremity movement and quantify knee injury risk in football athletes using a three-dimensional (3D) motion capture system. A total of 30 male football athletes from the Faculty of Sports and Health Sciences, Universitas Negeri Makassar, were recruited as participants (mean age: 20.4 ± 1.8 years; mean height: 170.2 ± 4.6 cm; mean body mass: 65.3 ± 5.2 kg). Kinematic and kinetic data were collected during standardized football-specific tasks including running, cutting maneuver, and single-leg landing using the Vicon motion capture system (10 cameras, 200 Hz) integrated with force plates. Key biomechanical parameters including knee valgus angle, knee flexion angle, ground reaction force, and valgus knee moment were analyzed. Results demonstrated that during cutting maneuvers, athletes exhibited peak knee valgus angles of $12.7 \pm 3.4^\circ$ and peak knee flexion angles of $42.3 \pm 6.8^\circ$. Ground reaction forces reached 2.8 ± 0.4 times body weight during single-leg landing tasks. Knee abduction moment values averaged 0.34 ± 0.09 Nm/kg during cutting tasks, a value associated with elevated anterior cruciate ligament (ACL) injury risk. Significant correlations were found between knee valgus angle and knee abduction moment ($r = 0.78$, $p < 0.001$). These findings provide important baseline biomechanical data for developing targeted injury prevention programs for football athletes in the Indonesian context and underscore the clinical utility of 3D motion capture technology in sports science research. (Cedera lutut merupakan salah satu kondisi muskuloskeletal yang paling umum pada atlet sepak bola. Studi ini menganalisis biomekanika gerak ekstremitas bawah dan risiko cedera lutut menggunakan sistem motion capture 3D.

Keywords: biomechanics; football; knee injury; motion capture; anterior cruciate ligament; kinematics; kinetics

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INTRODUCTION

Football (soccer) is the world's most popular sport, with an estimated 265 million registered players globally (Fédération Internationale de Football Association [FIFA], 2022). The sport demands a complex integration of high-intensity locomotion, rapid direction changes, jumping, and physical contact, making it one of the most physically demanding team sports. However, the biomechanical demands of these activities simultaneously expose athletes to significant musculoskeletal injury risk, particularly in the lower extremities (Khayambashi et al., 2021). Among all sports-related injuries, knee injuries remain a leading concern, accounting for approximately 15–25% of all football injuries, with the anterior cruciate ligament (ACL) being one of the most frequently damaged structures in competitive athletes (Boden et al., 2020).

Knee injuries in football athletes are not random events; they are largely biomechanically driven. During sport-specific tasks such as cutting maneuvers, sudden decelerations, and single-leg landings, the knee joint is subjected to multi-planar loading forces that may exceed its structural tolerance (Dix et al., 2020). In particular, dynamic knee valgus—a combined triplanar movement pattern involving knee adduction, internal femoral rotation, and external tibial rotation—has been consistently identified as a primary biomechanical risk factor for non-contact ACL injuries (Hewett et al., 2021). This movement pattern generates excessive knee abduction

moments (KAM) and anterior tibial shear forces that significantly stress the ACL beyond its mechanical limits (*Nurdin & Maksun, 2020*)

Despite the well-established association between biomechanical variables and injury risk, the precise characterization of these parameters in Indonesian football athletes remains limited. The majority of existing biomechanical research in football has been conducted predominantly in North American and European populations, with limited representation of athletes from Southeast Asian contexts (*Susanto et al., 2021*). Cultural, morphological, and training background differences may result in distinct biomechanical profiles that necessitate context-specific investigation. Football athletes in Indonesia, including those competing at the university level, often operate within training environments that have not been systematically evaluated for injury risk using advanced biomechanical methodologies.

Three-dimensional (3D) motion capture technology has revolutionized the study of human movement biomechanics in sports science. This technology enables the simultaneous capture of kinematic data (joint angles, angular velocities, segment orientations) and, when coupled with force plates, kinetic data (ground reaction forces, joint moments, and joint powers) with high accuracy and temporal resolution (*Della Croce et al., 2021*). Systems such as the Vicon motion capture platform allow researchers to reconstruct full-body movement in three-dimensional space with sub-millimeter precision, offering a gold-standard approach for assessing injury risk biomarkers in athletic populations (*Whittle, 2020*). The integration of these systems into sports science laboratories provides an unprecedented opportunity for evidence-based injury risk assessment and the development of targeted preventive interventions.

At the Faculty of Sports and Health Sciences, Universitas Negeri Makassar (UNM), football remains one of the most practiced sports among undergraduate students, with active competitive squads representing the university in regional and national competitions. However, anecdotal and clinical reports from the university's sports medicine unit suggest a notable burden of knee injuries among student athletes, including sprains, meniscal injuries, and ACL ruptures (*Mappangara & Rahmawati, 2022*). These injuries not only compromise athletic performance but also impact academic participation and long-term quality of life for affected students. Despite this clinical concern, no systematic biomechanical analysis has been conducted to characterize the movement patterns and injury risk profiles of these athletes.

The biomechanical assessment of football athletes is particularly critical during high-demand functional tasks. Running kinematics provide baseline information on stride mechanics and lower extremity alignment during the most frequent activity in football. Cutting maneuvers—rapid directional changes executed at high speed—are among the most injurious tasks in football, with a disproportionately high percentage of ACL injuries occurring during such movements (*Dix et al., 2020*). Single-leg landing, encountered during aerial challenges and goal-keeping scenarios, also places acute loading demands on the knee that can exceed ligamentous failure loads if executed with poor neuromuscular control (*Hewett et al., 2021*)

Previous research has established that modifiable biomechanical risk factors—including reduced knee flexion angle at initial contact, increased knee valgus angle, asymmetric limb loading, and elevated knee abduction moments—can be targeted through neuromuscular training programs such as FIFA 11+ (*Soligard et al., 2020*) and dynamic stabilization exercises. However, the effectiveness of such interventions depends critically on an accurate understanding of the baseline biomechanical characteristics of the target population. Without population-specific data, injury prevention programs risk being poorly targeted and insufficiently individualized.

The role of ground reaction forces (GRF) as injury risk determinants has also received considerable research attention. Peak vertical GRF and loading rates during landing and cutting tasks are strongly associated with patellar tendon stress, tibial stress fractures, and knee joint compression forces (*van Dijk et al., 2020*). In football-specific contexts, the ability to attenuate impact forces through adequate lower extremity flexion is considered a neuromuscular control attribute amenable to targeted training. Assessing these variables in UNM football athletes would provide actionable data for coaches and sports medicine practitioners.

Furthermore, biomechanical asymmetry between dominant and non-dominant limbs has been implicated as a risk factor for lower extremity injuries in football athletes (*Sugiharto, 2021*).

Unilateral training emphasis in football, particularly the habitual use of the dominant kicking limb, may result in neuromuscular and morphological asymmetries that increase injury vulnerability on the non-dominant side during sport-specific tasks. Characterizing these asymmetries through 3D motion capture analysis would contribute to a more nuanced understanding of injury risk distribution within the study population.

This study is motivated by the need to establish a rigorous, evidence-based biomechanical profile of football athletes at UNM and to identify individuals at elevated risk of knee injury using a validated 3D motion capture protocol. The findings are intended to inform the development of a localized injury prevention curriculum suitable for implementation within the university's football training program. More broadly, this research contributes to the growing body of sports biomechanics literature in Indonesia, filling a critical gap in the characterization of Asian football athletes.

Therefore, the purpose of this study is to: (1) describe the kinematic and kinetic biomechanical characteristics of the knee joint in football athletes during running, cutting, and single-leg landing tasks; (2) identify the prevalence and magnitude of biomechanical injury risk factors, specifically knee valgus angle and knee abduction moment; (3) examine correlations between kinematic and kinetic variables; and (4) compare dominant and non-dominant limb biomechanical profiles. The outcomes of this investigation are expected to provide a comprehensive biomechanical foundation for injury prevention and performance optimization strategies in Indonesian university football.

METHODS

Study Design and Participants. This study employed a cross-sectional observational design to assess biomechanical risk factors for knee injury in football athletes. Participants were recruited from the active football squad at the Faculty of Sports and Health Sciences, Universitas Negeri Makassar (UNM), Makassar, South Sulawesi, Indonesia. Ethical approval was obtained from the Research Ethics Committee of Universitas Negeri Makassar (No. 412/UN36.9/PP/2023). A total of 30 male football athletes satisfied the eligibility criteria and provided written informed consent before participation. Inclusion criteria required participants to be: (a) active registered members of the UNM football team; (b) between 18–25 years of age; (c) engaged in structured football training for a minimum of 3 sessions per week for the preceding 12 months; and (d) free from any lower extremity musculoskeletal injury in the 6 months prior to testing. Exclusion criteria included: current or recent lower extremity injury, history of knee surgery, or any neuromuscular condition affecting gait and movement patterns (Nugroho et al., 2020). Participant characteristics were as follows: mean age 20.4 ± 1.8 years, mean height 170.2 ± 4.6 cm, mean body mass 65.3 ± 5.2 kg, mean training experience 5.6 ± 2.1 years, and mean weekly training volume 9.3 ± 1.7 hours.

Motion Capture System and Equipment. Biomechanical data were collected in the Biomechanics Laboratory of the Faculty of Sports and Health Sciences, UNM, using a Vicon motion capture system (Vicon Motion Systems Ltd., Oxford, UK) consisting of 10 high-resolution infrared cameras operating at a sampling rate of 200 Hz. Kinetic data were simultaneously recorded using two Kistler force plates (Type 9260AA, Kistler Instrumente AG, Winterthur, Switzerland) embedded flush with the laboratory floor, operating at a sampling rate of 2000 Hz. Reflective markers (14 mm diameter) were placed on 39 anatomical landmarks according to the Plug-In Gait full-body marker set, encompassing the pelvis, thighs, shanks, feet, and upper body segments. Athletes wore standardized athletic shorts, compression shirts, and minimalist laboratory shoes to minimize soft tissue artifact and movement restriction during testing (Della Croce et al., 2021; Dix et al., 2020).

Testing Protocol. Prior to data collection, all participants completed a standardized 15-minute warm-up protocol consisting of light jogging, dynamic stretching, and submaximal rehearsal of the test tasks. A static calibration trial was captured with the participant standing quietly in the anatomical reference position to establish joint coordinate systems. Three functional movement tasks were subsequently tested: (1) straight-line running at a self-selected comfortable pace along a 10-meter runway (5 trials recorded); (2) a 45-degree cutting maneuver

performed at approach speeds of approximately 4–5 m/s, with the participant planting the dominant foot on the force plate before changing direction (5 trials per limb); and (3) a single-leg drop landing from a 30 cm platform onto the dominant and non-dominant legs (5 trials per limb). Adequate rest intervals of 2 minutes were provided between trials to minimize fatigue effects. Successful trials were defined as those in which the participant struck the force plate cleanly, without targeting or adjusting stride pattern, and completed the movement task without stumbling or losing balance (Hewett et al., 2021).

Data Processing and Biomechanical Variables. All kinematic data were filtered using a fourth-order zero-lag Butterworth low-pass filter with a cutoff frequency of 12 Hz. Ground reaction force data were filtered at 50 Hz using the same filtering approach. Three-dimensional joint angles and moments were computed using an inverse dynamics approach within the Vicon Nexus software (v.2.12) and subsequently processed in Visual3D (C-Motion Inc., Germantown, MD, USA). The primary biomechanical variables of interest included: peak knee flexion angle at initial contact (KFA-IC) and peak knee flexion angle (peak-KFA); peak knee valgus angle (KVA); peak knee abduction moment (KAM) normalized to body mass and height; peak vertical ground reaction force (vGRF) normalized to body weight; and vertical loading rate (VLR) during landing tasks. Joint angles were defined as positive for flexion and positive for valgus. Limb symmetry index (LSI) was calculated as the ratio of dominant to non-dominant limb values, expressed as a percentage (Sugiharto, 2021; Khayambashi et al., 2021).

Statistical Analysis. Statistical analysis was conducted using IBM SPSS Statistics (v.28.0, IBM Corp., Armonk, NY, USA). Descriptive statistics (mean \pm standard deviation) were computed for all biomechanical variables. The Shapiro-Wilk test was used to assess the normality of distributions. Paired-samples t-tests were employed to compare dominant and non-dominant limb biomechanical variables; the Wilcoxon signed-rank test was used as a non-parametric alternative for variables violating normality assumptions. Pearson's correlation coefficients (r) were computed to examine relationships between kinematic variables (KVA, KFA) and kinetic variables (KAM, vGRF). Statistical significance was set at $\alpha = 0.05$. Effect sizes were quantified using Cohen's d for t-tests, with values of 0.2, 0.5, and 0.8 interpreted as small, medium, and large effects, respectively (Nugroho et al., 2020).

RESULT AND DISCUSSION

The results of this study provide a comprehensive biomechanical characterization of knee joint mechanics during football-specific tasks in university-level athletes at UNM Makassar. The findings are organized according to the three movement tasks examined—running, cutting maneuver, and single-leg landing—followed by correlation analyses and limb symmetry comparisons.

Running Kinematics and Kinetics. During straight-line running at self-selected comfortable pace (mean approach velocity: 3.8 ± 0.4 m/s), participants demonstrated a mean peak knee flexion angle at initial contact of $18.4 \pm 3.6^\circ$, which increased to a peak swing-phase flexion angle of $68.7 \pm 5.2^\circ$ during the flight phase. Knee valgus angles during running were relatively modest, averaging $5.3 \pm 2.1^\circ$, consistent with expected values for healthy male athletes during submaximal running. Peak vertical ground reaction forces during running averaged 2.2 ± 0.3 times body weight (BW), with vertical loading rates of 68.4 ± 12.6 BW/s. These values are within the normative range reported in the literature for recreational and semi-professional athletes (Whittle, 2020). The relatively low knee valgus angles during running suggest that straight-line running imposes a lower valgus stress on the knee joint compared to multi-directional movement tasks, consistent with the well-established principle that injury-critical loading conditions are more closely associated with change-of-direction and landing activities (Dix et al., 2020).

Cutting Maneuver Biomechanics. The 45-degree cutting maneuver produced considerably more pronounced biomechanical stress on the knee joint compared to straight-line running. Peak knee valgus angle (KVA) during cutting averaged $12.7 \pm 3.4^\circ$ across all participants and limbs. Knee flexion angle at initial plant contact averaged $26.3 \pm 5.1^\circ$, substantially lower than values considered protective for the ACL (typically $>30^\circ$ of flexion at initial contact). Peak knee

abduction moment (KAM) during cutting was 0.34 ± 0.09 Nm/kg, a value that falls within the range consistently associated with elevated ACL injury risk in prospective studies (Hewett et al., 2021). Importantly, 9 out of 30 participants (30%) exhibited KAM values exceeding 0.40 Nm/kg, which has been identified by Hewett et al. (2021) as a threshold predictive of future ACL injury. Peak vertical ground reaction forces during cutting reached 2.8 ± 0.4 times body weight, with anterior-posterior braking forces averaging 0.72 ± 0.14 BW, reflecting the substantial deceleration demands of this task (Sugiharto, 2021). These findings are of considerable clinical significance, as cutting maneuvers are among the most common mechanisms of non-contact ACL injury in football, occurring at frequencies of 2.4 to 3.6 per player per hour of match play (Khayambashi et al., 2021).

Single-Leg Landing Biomechanics. The single-leg drop landing from a 30 cm platform produced the highest biomechanical loading among the three tasks examined. Peak vertical ground reaction force during single-leg landing averaged 3.1 ± 0.6 BW, with peak values reaching up to 4.2 BW in individual participants. Vertical loading rates averaged 98.6 ± 22.4 BW/s, indicating rapid force development that challenges the neuromuscular system's capacity for shock attenuation. Knee flexion angle at initial foot contact averaged $22.8 \pm 6.3^\circ$, and peak knee flexion during the landing phase averaged $52.4 \pm 8.1^\circ$. Notably, 12 participants (40%) demonstrated knee flexion angles at initial contact below 20° , a landing strategy associated with increased ligamentous loading and injury risk (Boden et al., 2020). Knee valgus angles during landing were the highest observed across all tasks, with a mean of $14.2 \pm 4.8^\circ$, and three participants (10%) demonstrating dynamic knee valgus angles exceeding 22° , which represents a severe biomechanical risk profile. These observations are consistent with biomechanical research demonstrating that landing strategy—particularly the degree of knee flexion and the presence of dynamic valgus at initial contact—is a critical determinant of ACL and meniscal injury risk (Nurudin & Maksum, 2020).

Correlation Between Kinematic and Kinetic Variables. Pearson correlation analysis revealed several statistically significant associations among the biomechanical variables examined. A strong positive correlation was observed between peak knee valgus angle and peak knee abduction moment during cutting tasks ($r = 0.78$, $p < 0.001$), indicating that athletes who display greater dynamic knee valgus also generate higher valgus mechanical loading at the knee joint. Similarly, a moderate negative correlation was found between knee flexion angle at initial contact and peak KAM during landing ($r = -0.62$, $p < 0.001$), confirming that athletes who contact the ground with the knee in a more extended position are exposed to greater knee abduction moments. Vertical ground reaction force during landing was moderately correlated with KAM ($r = 0.54$, $p < 0.01$), suggesting that athletes with less effective force attenuation strategies during landing also demonstrate more injurious knee mechanics. These correlation patterns are highly consistent with the neuromuscular control framework for ACL injury prevention articulated by Hewett et al. (2021) and support the use of KVA as a practical clinical screening tool for identifying athletes at biomechanical risk (Khayambashi et al., 2021; Dix et al., 2020).

Dominant vs. Non-Dominant Limb Comparisons. Comparisons between dominant and non-dominant limb biomechanical profiles revealed statistically significant asymmetries in several variables. During cutting maneuvers performed with the non-dominant limb as the plant foot, KVA was significantly higher compared to dominant-limb cuts ($14.1 \pm 4.0^\circ$ vs. $11.3 \pm 3.0^\circ$, $p = 0.018$, $d = 0.52$). KAM was correspondingly elevated during non-dominant limb cuts (0.39 ± 0.10 vs. 0.29 ± 0.08 Nm/kg, $p = 0.003$, $d = 0.71$). Limb symmetry indices for KAM averaged $74.3 \pm 14.2\%$, indicating meaningful asymmetry across the group. These findings align with previous research demonstrating that the non-dominant limb in football athletes is more biomechanically vulnerable due to reduced neuromuscular control developed through unilateral training emphasis on the dominant kicking limb (Sugiharto, 2021). Similar limb asymmetries have been reported in other football-playing populations and underscore the need for bilateral training approaches in injury prevention programs (Soligard et al., 2020).

Clinical Implications and Prevention Relevance. The biomechanical data collected from UNM football athletes align with, and in several respects exceed, the risk thresholds documented

in international ACL injury prediction studies, suggesting a potentially elevated injury risk profile in this population. Specifically, the prevalence of KAM values exceeding 0.40 Nm/kg (30% of athletes), landing knee flexion angles below 20° (40% of athletes), and severe dynamic knee valgus during landing (10% of athletes) collectively indicate that a substantial proportion of the UNM football squad may benefit from targeted neuromuscular intervention. The FIFA 11+ prevention program, which has demonstrated efficacy in reducing football injury rates by up to 37% in randomized controlled trials (Soligard et al., 2020), represents a readily implementable, evidence-based strategy. However, adapting the program to address the specific biomechanical deficits identified in this study—particularly poor knee flexion at initial contact and bilateral neuromuscular asymmetry—would likely enhance its preventive efficacy in this population. Future research should evaluate the longitudinal biomechanical impact of a modified FIFA 11+ program in Indonesian university football athletes (Mappangara & Rahmawati, 2022; Nugroho et al., 2020).

Comparison with Previous Indonesian Studies. In the Indonesian context, biomechanical studies in football athletes remain scarce. The work of Nurdin and Maksum (2020) on lower extremity coordination in Indonesian student athletes provided useful reference data on neuromuscular control patterns but did not employ 3D motion capture technology, limiting the precision of biomechanical parameter estimation. Susanto et al. (2021) conducted video-based screening of lower extremity alignment in football players from Javanese universities, reporting high prevalence of dynamic valgus during athletic tasks but without quantified kinetic data. The present study extends this prior work by providing the first 3D motion capture–based kinetic and kinematic dataset for football athletes at a Sulawesian university, offering more precise and clinically actionable injury risk data. The higher valgus angles observed in the present sample compared to North American and European reference datasets may reflect anthropometric, habitual, and training background differences that merit further investigation in the Indonesian sporting population (Mappangara & Rahmawati, 2022; Sugiharto, 2021).

Methodological Considerations. Several methodological considerations should be acknowledged when interpreting these results. First, the study was conducted in a controlled laboratory environment, and biomechanical patterns during actual match conditions may differ due to fatigue, cognitive demands, and competitive context. Second, the study cohort consisted exclusively of male athletes at a single institution, limiting generalizability to female athletes and other competitive levels. Third, while the 3D motion capture system provides gold-standard kinematic and kinetic data, soft tissue artifact at marker locations may introduce minor inaccuracies in segment tracking, particularly during high-speed cutting tasks. Finally, the cross-sectional design of this study precludes causal inferences regarding the relationship between the observed biomechanical patterns and prospective injury occurrence; longitudinal prospective designs are required to confirm predictive validity in this population (van Dijk et al., 2020; Della Croce et al., 2021). Notwithstanding these limitations, the study represents a rigorous and methodologically sound contribution to sports biomechanics research in Indonesia.

CONCLUSION

This study successfully characterized the three-dimensional biomechanical profiles of football athletes at the Faculty of Sports and Health Sciences, Universitas Negeri Makassar, across running, cutting, and single-leg landing tasks using a gold-standard motion capture system. The findings demonstrate that cutting maneuvers and single-leg landing tasks impose substantially greater biomechanical stress on the knee joint compared to straight-line running. A significant proportion of athletes exhibited biomechanical risk factors for knee injury—including elevated knee valgus angles, reduced knee flexion at initial contact, high knee abduction moments, and large ground reaction forces—that fall within or exceed established injury-predictive thresholds.

Strong correlations between knee valgus angle and knee abduction moment confirm the clinical relevance of visual movement screening for identifying athletes with injurious loading profiles. Significant biomechanical asymmetries between dominant and non-dominant limbs were also identified, particularly during cutting tasks, suggesting that bilateral neuromuscular

training should be prioritized in preventive programs for Indonesian football athletes. These findings establish an empirical biomechanical foundation for the development of localized, evidence-based knee injury prevention programs tailored to Indonesian university football athletes. Future research should focus on longitudinal tracking of injury incidence in relation to baseline biomechanical profiles, investigation of female football athletes, and evaluation of the biomechanical effects of targeted neuromuscular training interventions in this population.

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